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Constraints on dark photons from π^0 decays

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Several models of dark matter suggest the existence of hidden sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields. The interaction between the ordinary and hidden sectors could be transmitted by new Abelian $U'(1)$ gauge bosons A' (dark or hidden photons) mixing with ordinary photons. If such A''s have masses below the π^0 meson mass, they would be produced through $\gamma - A'$ mixing in the $\pi^0 \to \gamma\gamma$ decays and be observed via decays $A' \to e^+e^-$. Using bounds from the SINDRUM experiment at the Paul Scherrer Institute that searched for an excess of e^+e^- pairs in $\pi^- p$ interactions at rest, the area excluding the $\gamma - A'$ mixing $\epsilon \gtrsim 10^{-3}$ for the A' mass region $25 \lesssim M_{A'} \lesssim 120$ MeV is derived.

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The origin of dark matter is still a great puzzle in particle physics and cosmology. Several models dealing with this problem suggest the existence of 'hidden' sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields. These sectors do not interact with our world directly and couple to it by gravity. It is also possible that there exist new very-weak forces between the ordinary and dark worlds transmitted by new Abelian $U'(1)$ gauge bosons A' (dark or hidden photons for short) mixing with our photons [1], as discussed first by Okun in his model of paraphotons [2]. In a class of recent interesting models the $\gamma - A'$ mixing strength may be large enough to be experimentally tested. This makes searches for A''s very attractive; for a recent review see [3] and references therein.

It should be noted, that many models of physics beyond the Standard Model (SM) such as GUTs [4], superstring models [5] (see also Ref.[6]), supersymmetric [7], and models including the fifth force [8] also predict an extra $U^{'}(1)$ factor and the corresponding new gauge X boson. The X's could interact directly with quarks and/or leptons. If the X mass is below the pion mass, the X could be effectively searched for in the decays $P \to \gamma X$, where $P = \pi^0, \eta$, or η'. This is due to the fact, that the decay rate of $P \to \gamma$ + *any new particles with spin 0 or* $\frac{1}{2}$ is proved to be negligibly small [9]. Hence, an observation of these decay modes could unambiguously signal the discovery of a new spin-1 boson, in contrast with other searches for new light particles in rare K, π or μ decays [9–11].

The allowed $\gamma - A'$ interaction is given by the kinetic mixing [2, 3, 12, 13]

$$L_{int} = -\frac{1}{2}\epsilon F_{\mu\nu} A'^{\mu\nu} \tag{1}$$

where $F^{\mu\nu}$, $A'^{\mu\nu}$ are the ordinary and the dark photon fields, respectively, and ϵ is their mixing strength. In some recent dark matter models the dark photon could be massless; see, e.g. Refs.[14, 15]. If the A' has a mass, the kinetic mixing of Eq.(1) can be diagonalized resulting in a nondiagonal mass term and $\gamma - A'$ mixing. Hence, any γ-source could produce a kinematically allowed massive A' boson according to the appropriate mixings. Then, if the mass difference is small, ordinary photons may oscillate into dark photons-similarly to neutrino oscillations- or, if the mass difference is large, dark photons could decay, e.g. into e^+e^- pairs.

Experimental constaints on dark photons in the meV-keV mass range can be derived from searches for the fifth force [2, 16, 17], from experiments based on the photon regeneration technique [18–22], and from astrophysical considerations [23, 24]. For example, the results of experiments searching for solar axions [25, 26] can be used to set limits on the $\gamma - A'$ mixing in the keV part of the solar spectrum of dark photons [27–30]. Stringent bounds on the low mass A's could be obtained from astrophysical considerations [31]-[33]. There are plans to test the existence of sub-eV dark photons at new facilities, such as, for example, SHIPS [34] and IAXO [35].

The A''s with the masses in the sub-GeV range, see e.g. [36–38], can be searched for through their $A' \to e^+e^-$ decays in beam-dump experiments [39–44], or in particle decays [45–48]. Recently, stringent bounds on the mixing ϵ have been obtained from searches for decay modes $\pi^0, \eta, \eta' \to \gamma A'(X)$, $A'(X) \to e^+e^-$ with existing data of neutrino experiments [49, 50]. These limits are valid for the relatively long-lived A's with a mixing strength in the range $10^{-4} \lesssim \epsilon \lesssim 10^{-7}$. The goal of this note is to show that new bounds on the decay $\pi^0 \to \gamma A'$ of neutral pions into a photon and a short-lived A' followed by the rapid decay $A' \to e^+e^-$ due to the relatively large $\gamma - A'$ mixing can be obtained from the results of sensitive searches for an excess of single isolated e^+e^- pairs from decays of the weakly interacting neutral boson X by the SINDRUM Collaboration at the Paul Scherrer Institute (PSI, Switzerland) [51].

The SINDRUM experiment- specifically designed to search for rare particle decays in the SINDRUM magnetic spectrometer- was performed by using the $\pi^- p$ interactions at rest as the source of π^0's. The π^0's were produced in the charge exchange reaction $\pi^- p \to \pi^0 n$ of 95 MeV/c π^-'s stopped in a small liquid hydrogen target in the center of the SINDRUM magnetic spectrometer. The magnetic field was 0.33 T, resulting in a transverse-momentum threshold of roughly 17 MeV/c for

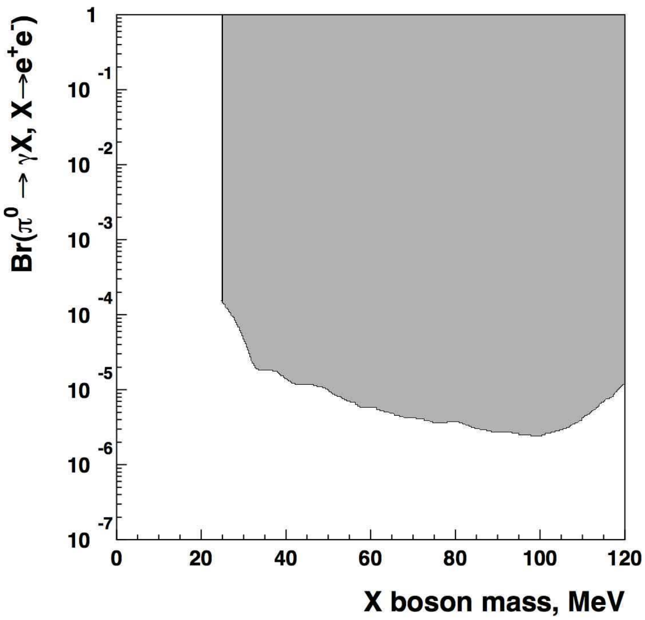

FIG. 1: The 90 % C.L. area (shaded) in the $\big(M_X; Br(\pi^0 \to \gamma X, X \to e^+e^-)\big)$ plane excluded by the SINDRUM experiment (from Ref.[51]).

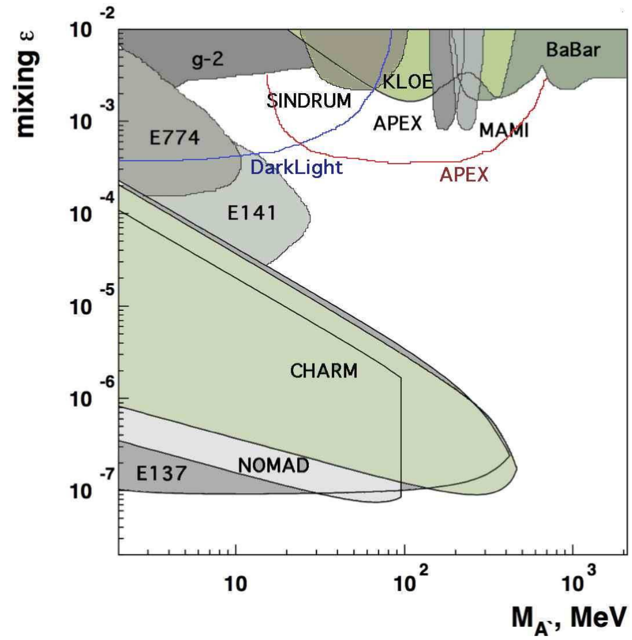

FIG. 2: Exclusion region in the $(M_{A'}; \epsilon)$ plane obtained in the present work from the results of the SINDRUM experiment [51]. Shown are areas excluded from the muon (g-2) considerations, by the results of the electron beam-dump experiments E137 [39, 41], E141 [42], E774 [43], the searches in APEX [44], KLOE[46], BaBar[47], and MAMI [48], and from the data of the neutrino experiments NOMAD [49] and CHARM [50]. Expected sensitivities of the planned APEX (full run) and DarkLight experiments are also shown for comparison. For a review of all experiments, which intend to probe a similar parameter space, see Ref.[52] and references therein.

particles reaching the scintillator hodoscope surrounding the target. The trigger required an e^+e^- pair with an opening angle in the plane perpendicular to the beam axis of at least 35^o; this corresponds to a lower threshold in the invariant mass of 25 MeV/c [51]. A total of 98 400 $\pi^0 \to \gamma e^+e^-$ decays were observed. The signature of the $X \to e^+e^-$ decay would be seen as a peak in the continuous e^+e^- invariant mass distribution.

No such peak events were found and upper limits on the branching ratio $Br(\pi^0 \to \gamma X, X \to e^+e^-) = \frac{\Gamma(\pi^0 \to \gamma X, X \to e^+e^-)}{\Gamma(\pi^0 \to \gamma\gamma)}$ in the range $\simeq 10^{-6} - 10^{-5}$ have been placed for the X-mass region $25 \lesssim M_X \lesssim 120$ MeV. The corresponding 90% C.L. exclusion area in the $\big(M_X; Br(\pi^0 \to \gamma X, X \to e^+e^-)\big)$ plane is shown in Fig.1. The limits were obtained assuming the X lifetimes to be in the range

$$10^{-23} \lesssim \tau_X \lesssim 10^{-11} \text{ s.} \tag{2}$$

For lower values of τ_X in Eq.(2) the e^+e^- mass peak would be smeared out beyond recognition; for larger values most X's would decay outside the target region and thus the detector would not be triggered [51].

If the A' exists and is a short-lived particle, it would decay in the SINDRUM target and be observed in the detector via the $A' \to e^+e^-$ decay similar to the decays of X's. The occurrence of $A' \to e^+e^-$ decays would appear as an excess of e^+e^- pairs in the SINDRUM spectrometer above those expected from standard decays of π^0 produced in π^-p interactions. As the final states of the decays $\pi^0 \to \gamma X, X \to e^+e^-$ and $\pi^0 \to \gamma A', A' \to e^+e^-$ are identical, the results of the searches for the former can be used to constrain the latter for the same e^+e^- invariant mass regions.

For a given number N_{π^0} of π^0's produced in the target the expected number of $A' \to e^+e^-$ (or $X \to e^+e^-$) decays occuring within the fiducial volume of the SINDRUM detector is given by

$$\begin{aligned} N_{A' \to e^+e^-}(M_{A'}) &= \int f\Big[1 - \exp\Big(-\frac{rM_{A'}}{P\tau_{A'}}\Big)\Big]\zeta A dr d\Omega \\ &= N_{\pi^0} Br(\pi^0 \to \gamma A') Br(A' \to e^+e^-)\zeta A \end{aligned} \tag{3}$$

where $M_{A'}$, P, f, r, $\tau_{A'}$ are the A' mass, momentum, flux, the distance between the A' decay vertex and the target, and the lifetime at rest, respectively and ζ and A are the e^+e^- pair reconstruction efficiency and the acceptance of the SINDRUM spectrometer, respectively [51]. Here it is assumed that the A' is a short-lived particle with $\frac{rM_{A'}}{P\tau_{A'}} \gg 1$ for r values larger than the effective size of the target, in accordance with Eq.(2). Taking Eq.(3) into account and using the relation $N_{A' \to e^+e^-}(M_{A'}) <$

$N^{90\%}_{e^+e^-}(M_{A'})$, where $N^{90\%}_{e^+e^-}(M_{A'})$ is the 90% C.L. upper limit for the number of signal events from the decays of the A' with a given mass $M_{A'}$, results in the 90% C.L. exclusion area in the $(M_{A'}; Br(\pi^0 \to \gamma A', A' \to e^+e^-))$ plane obtained by the SINDRUM experiment and shown in Fig.1. The upper limit $N^{90\%}_{e^+e^-}$ as a function of $M_{A'}$ was obtained from the fit of the measured e^+e^- mass distribution in the vicinity of each selected value of $M_{A'}$, to a sum of the signal peak from the $A' \to e^+e^-$ decays and a flat background distribution.

The obtained results can be used to impose bounds on the $\gamma - A'$ mixing strength as a function of the dark photon mass. For A' masses smaller than the mass M_{π^0} of the π^0 meson, the branching fraction of the decay $\pi^0 \to \gamma A'$ is given by [36]:

$$Br(\pi^0 \to \gamma A') = 2\epsilon^2 Br(\pi^0 \to \gamma\gamma)\Big(1 - \frac{M^2_{A'}}{M^2_{\pi^0}}\Big)^3. \quad (4)$$

Assuming that the dominant A'-decay is into a e^+e^- pair, the corresponding decay rate is given by:

$$\Gamma(A' \to e^+e^-) = \frac{\alpha}{3}\epsilon^2 M_{A'}\sqrt{1 - \frac{4m_e^2}{M^2_{A'}}}\Big(1 + \frac{2m_e^2}{M^2_{A'}}\Big) \quad (5)$$

Taking into account Eq.(4), one can determine the 90% C.L. exclusion area in the $(M_{A'}; \epsilon)$ plane from the results of the SINDRUM experiment. This area is shown in Fig. 2, together with regions excluded by the results of the electron beam-dump experiments E137, E141, E774 [39, 41–43], by recent measurements from APEX [44], KLOE [46], BaBar [47], and MAMI [48], and from the data of the neutrino experiments NOMAD [49] and CHARM [50]. For a recent, more detailed review of existing and planned limits, see Refs. [52–54]. The shape of the exclusion contour from the SINDRUM experiment corresponding to the A' masses $M_{A'} \gtrsim 100$ MeV is defined mainly by the phase-space factor in Eq.(4). The A' lifetime values calculated by using Eq.(5) for the mass range $25 \lesssim M_X \lesssim 120$ MeV are found to be within the allowed range of Eq.(2). Note, that since the A' is a short-lived particle, the sensitivity of the search is $\propto \epsilon^2$, differently from the case of a long-lived A', where the number of signal events is $\propto \epsilon^4$; see, e.g. Refs.[49, 50].

In summary, using results from the SINDRUM experiments on the search for weakly interacting X bosons produced in $\pi^- p$ interactions at rest and decaying into e^+e^- pairs, new bounds on a hidden-sector gauge A' boson produced in the decay $\pi^0 \to \gamma A'$ were derived. The obtained exclusion area covers the A' mass region $25 \lesssim M_{A'} \lesssim 120$ MeV and the $\gamma - A'$ mixing strength $\epsilon \gtrsim 10^{-3}$.

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[1] M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B **662**, 53 (2008); E. J. Chun, J. C. Park and S. Scopel, JHEP **1102**, 100 (2011); Y. Mambrini, JCAP **1107**, 009 (2011); D. Hooper, N. Weiner and W. Xue, Phys. Rev. D **86**, 056009 (2012).

[2] L.B. Okun, Sov. Phys. JETP **56**, 502 (1982) [Zh. Eksp. Teor. Fiz. **83**, 892 (1982)].

[3] J. Jaeckel and A. Ringwald, Ann. Rev. Nucl. Part. Sci. **60**, 405 (2010).

[4] P. Langacker , Phys. Rep. **72** C, 185 (1981).

[5] J. Ellis et al., Nucl. Phys. B **276**, 14 (1986).

[6] M.Yu.Khlopov and K.I.Shibaev, Grav. Cosm. Suppl, **8**, 45 (2002).

[7] S. Weinberg , Phys. Rev. D **26**, 287 (1982); P. Fayet, Nucl.Phys. B **187**, 184 (1981).

[8] E.D. Carlson, Nucl. Phys. B **286**, 378 (1987).

[9] M.I. Dobroliubov and A.Yu. Ignatiev, Nucl. Phys. B **309**, 655 (1988); Phys. Lett. B **206**, 346 (1988).

[10] M.I. Dobroliubov, Yad. Fiz. **52**, 551(1990); [Sov. J. Nucl. Phys. **52**, 352 (1990)]; Z. Phys. C **49**, 151 (1991).

[11] S.N. Gninenko and N.V. Krasnikov, Phys. Lett. B **513**, 119 (2001).

[12] B. Holdom, Phys. Lett. B **166**, 196 (1986).

[13] R. Foot and X.G. He, Phys. Lett. B **267**, 509 (1991).

[14] J. M. Cline, Z. Liu, and W. Xue, Phys. Rev. D **85**, 101302 (2012) [arXiv:1201.4858 [hep-ph]].

[15] J. M. Cline, Z. Liu, and W. Xue, Phys. Rev. D **87**, 015001 (2013) [arXiv:1207.3039 [hep-ph]].

[16] E.R. Williams, J.E. Faller, and H.A. Hill, Phys. Rev. Lett. **26**, 721 (1971).

[17] D.F. Bartlett and S. Loegl, Phys. Rev. Lett. **61**, 2285 (1988).

[18] A.A. Anselm, Yad. Fiz. **42**,1480 (1985); Sov. Journ. Nucl. Phys. **42**, 936 (1985).

[19] K. Van Bibber et al., Phys. Rev. Lett. **59**, 759 (1987).

[20] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983); idid **52**, 695 (1984).

[21] G. Raffelt and L. Stodolsky, Phys. Rev. D**37**, 1237 (1988).

[22] K. Van Bibber et al., Phys. Rev. D**39**, 2089 (1989).

[23] V.Popov and O.Vasil'ev, Europhys. Lett. **15**, 7 (1991).

[24] V. Popov, Turkish Journal of Physics **23**, 943 (1999).

[25] K. Zioutas et al.(CAST Collaboration), Phys. Rev. Lett. **94**, 121301 (2005).

[26] S. Andriamonje et al.(CAST Collaboration), JCAP **0704**, 010 (2007).

[27] J. Redondo, JCAP **0807**, 008 (2008).

[28] J. Redondo, arXiv:1202.4932.

[29] S.N. Gninenko and J. Redondo, Phys. Lett. B **664**, 180 (2008).

[30] S.V. Troitsky, arXiv:1112.5276.

[31] S.I. Blinnikov and M.I. Visotsky, Yad. Fiz. **52**, 544 (1990); Sov. J. Nucl. Phys. **52**, 348 (1990).

[32] S. Davidson and M. Peskin, Phys. Rev. D **49**, 2114 (1994).

[33] S. Davidson, S. Hannestad, and G. Raffelt, JHEP **0005**, 003 (2000).

[34] M. Schwarz, A. Lindner, J. Redondo, A. Ringwald, and

G. Wiedemann, arXiv:1111.5797.
[35] I.G. Irastorza et al. (IAXO Collaboration), arXiv:1201.3849.
[36] B. Batell, M. Pospelov, and A. Ritz, Phys. Rev. D **80**, 095024 (2009).
[37] M. Reece and L.-T. Wang, JHEP **0907**, 051 (2009).
[38] M. Williams, C.P. Burgess, A. Maharana, and F. Quevedo, JHEP **1108**, 106 (2011).
[39] J.D.Bjorken et al. Phys. Rev. D **80**, 075018 (2009)
[40] J. Blümlein and J. Brunner, Phys. Lett. B **701**, 155 (2011).
[41] J.D. Bjorken et al., Phys. Rev. D **38**, 3375 (1988).
[42] E. M. Riordan et al., Phys. Rev. Lett. **59**, 755 (1987).
[43] A. Bross, M. Crisler, S. H. Pordes, J. Volk, S. Errede and J. Wrbanek, Phys. Rev. Lett. **67**, 2942 (1991).
[44] S. Abrahamyan et al., Phys. Rev. Lett. **107**, 191804 (2011).
[45] H.-B. Li and T. Luo, Phys. Lett. B **686**, 249 (2010).
[46] F. Archilli et al., Phys. Lett. B **706**, 251 (2012).
[47] B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. **103**, 081803 (2009).
[48] H. Merkel et al., Phys. Rev. Lett. **106**, 251802 (2011).
[49] S.N. Gninenko, Phys. Rev. D **85**, 055027 (2012).
[50] S.N. Gninenko, Phys. Lett. B **713**, 244 (2012).
[51] R. Meijer Drees et al.(SINDRUM Collaboration), Phys. Rev. Lett. **68**, 3845 (1992).
[52] J.L. Hewett et al., arXiv:1205.2671.
[53] S. Andreas, C. Niebuhr, and A. Ringwald, Phys. Rev. D **86**, 095019 (2012).
[54] S. Andreas, arXiv:1211.5160 [hep-ph].